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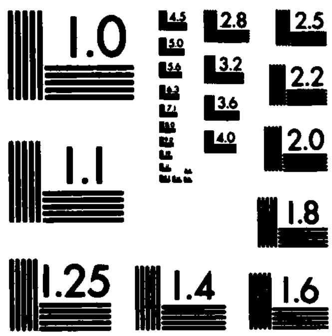

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FOR LOW TEMPERATURE ELECTRONICS CIRCUITS

COLD END TEST
CONTRACT N00014-82-C-0326

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CONTRACT N00014-82-C-0326

CTI-CRYOGENICS
A Division of Helix Technology Corporation
Kelvin Park
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Final Report

August 1983

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This experimental test program was conducted under Office of Naval Research contract N00014-82-C-0326 to test the thermodynamic performance of the MACOR™ cold end of a cryocooler design suitable for use with superconductive and other low temperature electronics circuits. The cold end of the test cryocooler was based directly on the design of the cryocooler as reported in the final report of the Phase II Preliminary Design program (contract N00014-81-C-0525). The experimental investigation was concerned

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only with the thermodynamic performance of the cold end and not with vibration and magnetic signature requirements given in the preliminary design final report.

A fabricated MACOR™ cold end including a metallic coating to prevent helium permeation and a fabricated die post displacer support bearing were combined with a compressor and motor which are standard CTI-CRYOGENICS products. A mechanical test was performed on the test cryocooler to determine that the MACOR™ displacer was successfully guided by the die post bearing.

Thermodynamic tests were conducted to determine the lowest temperature of the 4th (coldest) stage as a function of operating speed, helium charge pressure, 4th stage electrical heat load, and transfer tube diameter. Cooldown and steady state results are reported.

Results indicate a low temperature limit of approximately 95K with the current test hardware. Although this represents an improvement from 122K during the program, a resizing will be necessary to reach 10K. The die post displacer support bearing and the MACOR™ cold finger construction are mechanically satisfactory. The metallic layer applied to the outside of the MACOR™ cylinder to prevent helium permeation was successful.

FOREWORD

This report is the technical document describing the work done under Office of Naval Research Contract N00014-82-C-0326. The report describes the experimental test program conducted to determine the thermodynamic performance of the MACOR™ cold end of the cryocooler designed under contract N00014-81-C-0525.

Technical contributions have been made by:

Dr. Peter J. Kerney, Program Manager
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ABSTRACT

This experimental test program was conducted under Office of Naval Research Contract N00014-82-C-0326 to test the thermodynamic performance of the MACOR^{TM} cold end of a cryocooler design suitable for use with superconductive and other low temperature electronics circuits. The cold end of the test cryocooler was based directly on the design of the cryocooler as reported in the final report of the Phase II Preliminary Design program (Contract N00014-81-C-0525). The experimental investigation was concerned only with the thermodynamic performance of the cold end and not with vibration and magnetic signature requirements given in the preliminary design final report.

A fabricated MACOR^{TM} cold end including a metallic coating to prevent helium permeation and a fabricated die post displacer support bearing were combined with a compressor and motor which are standard CTI-CRYOGENICS products. A mechanical test was performed on the test cryocooler to determine that the MACOR^{TM} displacer was successfully guided by the die post bearing.

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Results indicate a low temperature limit of approximately 95K with the current test hardware. Although this represents an improvement from 122K during the program, a resizing will be necessary to reach 10K. The die post displacer support bearing and the MACOR^{TM} cold finger construction are mechanically satisfactory. The metallic layer applied to the outside of the MACOR^{TM} cylinder to prevent helium permeation was successful.

I. INTRODUCTION

Application of superconductivity to electronics instrumentation offers many potential advantages including reduced input power, weight, and size. If these advantages are to be fully realized, the power requirement, weight, and size of the supporting refrigeration system must also be reduced. In addition, some candidate electronics applications are very sensitive to magnetic noise introduced by the cryocooler. Therefore, materials used in the cryocooler near the electronics for these applications should be non-ferromagnetic and electrically insulating. Ferromagnetic components such as the motor armature must be shielded to attenuate the magnetic noise.

Phase I of the present program performed under Contract N00014-80-C-0465 (Final Report Nov. 1980) successfully addressed the question of concept feasibility in applying cryogenic mechanical refrigeration to superconductive electronics devices. A primary concept partially constructed of a machinable glass ceramic (MACOR™) produced by Corning Glass Works was found to be thermodynamically acceptable; however, some design problems remained to be resolved. These included permeation of helium through MACOR™, magnetic signature of MACOR™, vibration abatement, and magnetic shielding of ferromagnetic components.

Phase II of the program, Contract N00014-81-C-0525 (Final Report August 1982) successfully resolved the design problems associated with the MACOR™ and with magnetic shielding. A preliminary design of the program cryocooler was presented in the final report. The preliminary design included a MACOR™ cold finger, die post bearing cantilever support of the displacer, and a balanced compressor system designed to minimize vibration.

The first step toward construction of a full prototype of the cryocooler design was accomplished in this present phase of the program. This step included construction and testing of a brassboard cold finger (displacer and cylinder assembly) supported by an existing compressor assembly. Mechanical and thermodynamic tests were conducted. The tests and results are described in this report.

Purpose

The purpose of this phase of the program was to construct and experimentally investigate a brassboard cold end of the cryocooler designed under contract N00014-81-C-0525.

Scope

The scope of the program included the following:

- Construct the MACOR^{TM} displacer and cylinder, and the die post bearing and housing.

- Perform a mechanical test to determine that vibration of the displacer relative to the cold cylinder is low enough that contact does not occur during operation.

- Perform thermodynamic tests sufficient to characterize the performance of the cold end.

II. TEST CRYOCOOLER DESIGN

The present program was concerned with the thermodynamic performance of a brassboard cold end; therefore, only the MACOR^{TM} displacer and cylinder with the outer metallic coating were constructed according to the design reported in the Contract N00014-81-C-0525 Final Report. A compressor and motor were selected from CTI-CRYOGENICS' product inventory. The die post bearing housing connecting the cold finger with the compressor was slightly modified to suit the compressor package selected.

The test cryocooler design is shown in Figure 1. The cold finger displacer and cylinder ① are constructed of MACOR^{TM}, a machinable glass ceramic manufactured by Corning Glass Works. The displacer is supported to reciprocate in the cylinder with a 0.004 inch radial gap by the die post bearing ② . A metallic coating was applied on the outside of the MACOR^{TM} cylinder to prevent loss of helium gas by permeation.

The die post bearing clearance of less than 150 $(10)^{-6}$ inches prevents the displacer from touching the cylinder in the cold regions. The die post bearing is functionally the same as described in the Phase II final report, but the geometry has been specially adapted to suit the present hardware.

The compressor and motor package ③ selected was from a standard CTI-CRYOGENICS 1 watt integral Stirling cryogenic cooler. The selection was based on achieving the correct displacement to operate the cold finger although the displacer stroke was increased from 0.1 inches to 0.15 inches to match the compressor stroke. The drive motor was tested separately on a dynamometer in order to determine that it would successfully power the test cooler. The compressor and motor housings are aluminum with a stainless steel compressor sleeve.

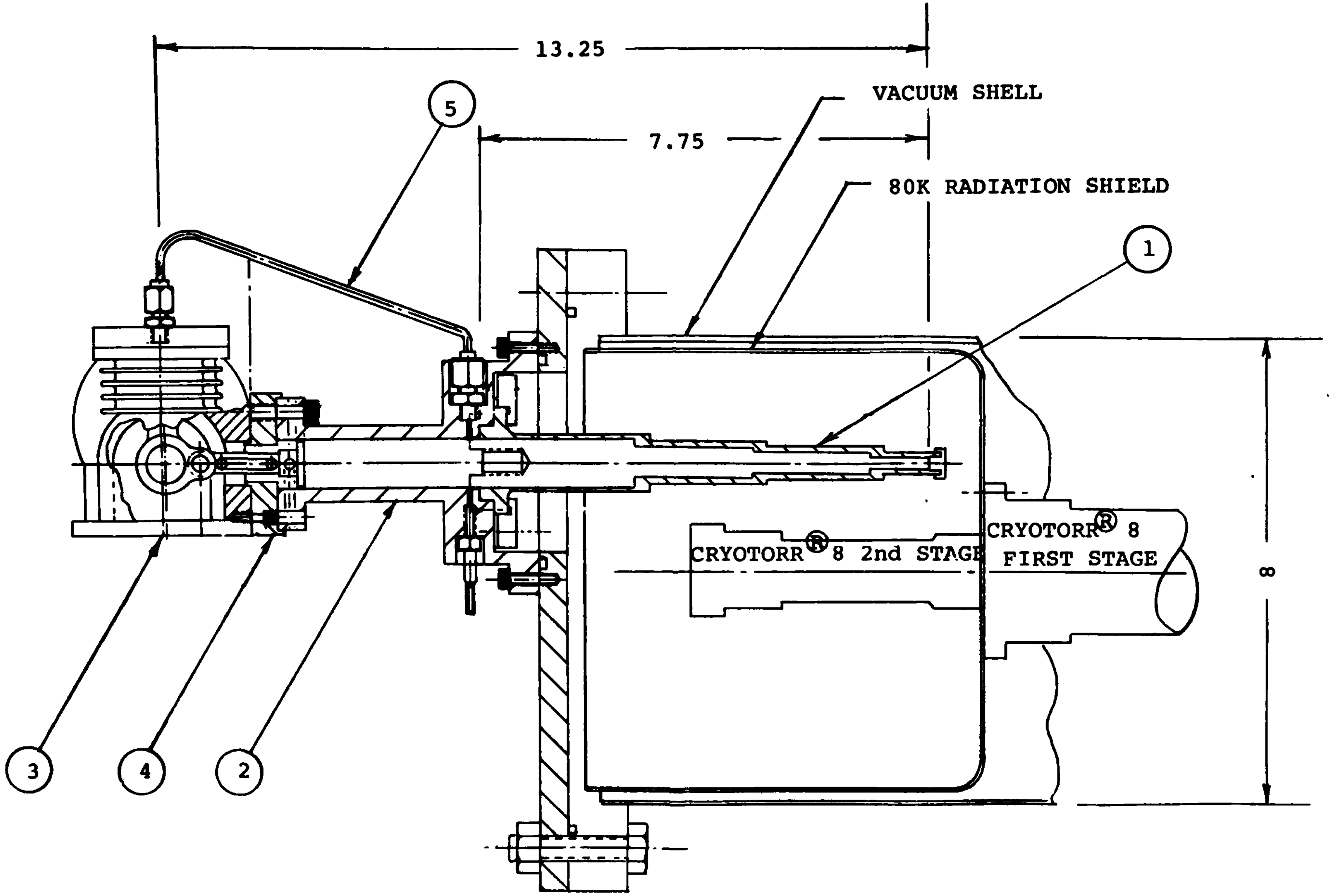


Figure 1. Test Cryocooler Design

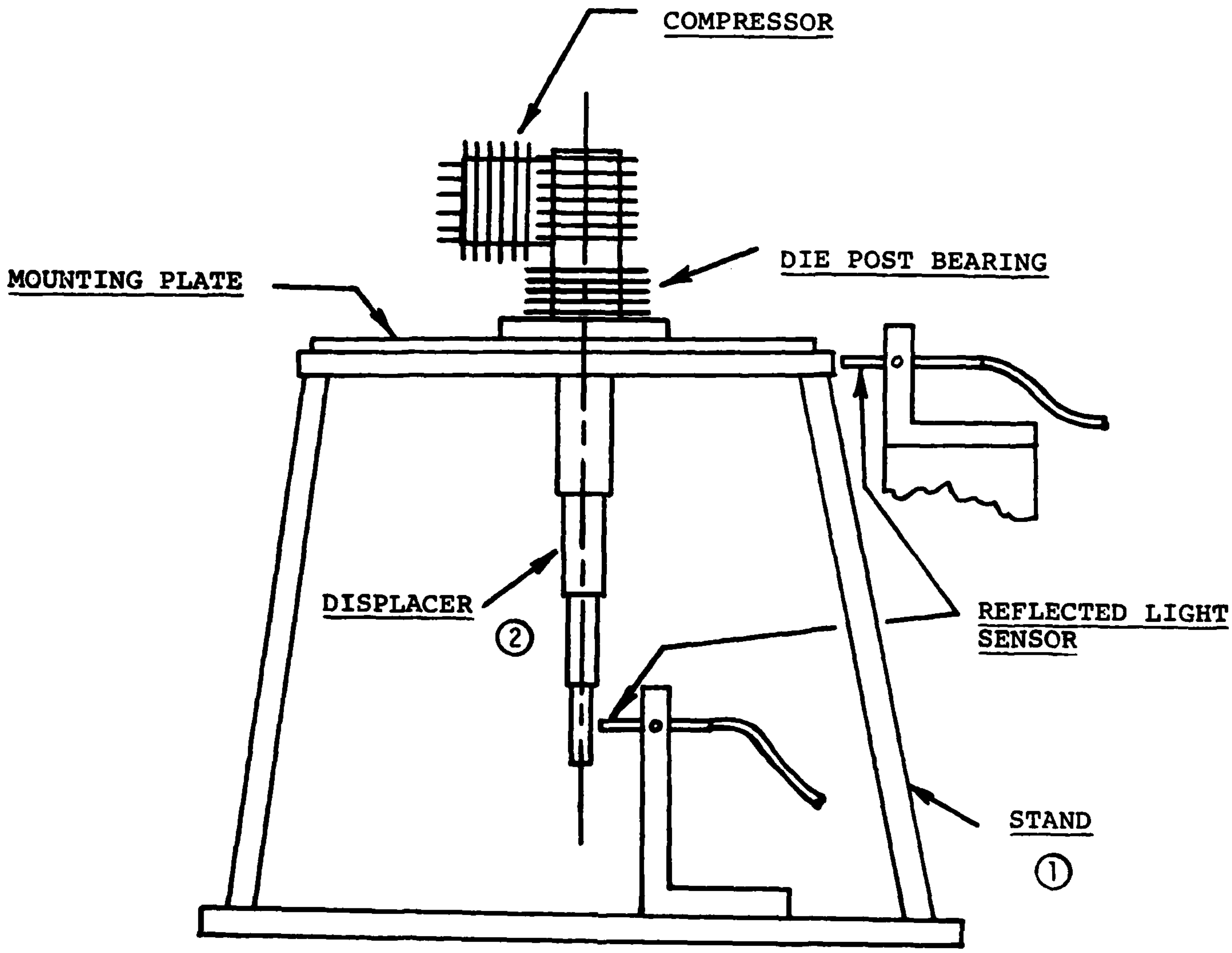
Adapters 4 between the compressor and die post bearing were specially designed and made of 304 stainless steel to provide the proper mounting. The diameter of the stainless steel transfer tube 5 was varied during the thermodynamic tests in order to optimize performance. An annular distribution gap 0.020 inches thick around the base of the displacer distributed the helium gas evenly to the 0.004 inch gap between the displacer and the cylinder.

III. MECHANICAL VIBRATION TESTS

The purpose of the mechanical vibration test was to determine that the die post bearing provided enough support to prevent the displacer from touching the cylinder during operation. The MACOR^{TM} cylinder was removed from the cryocooler for this test series and the cryocooler was operated in the supporting apparatus shown schematically in Figure 2.

The test stand ① supports the cryocooler ② with the displacer in a vertical position. A reflected light sensor (Fotonic Sensor Model KD320 manufactured by Mechanical Technology Inc., Latham, NY) detects lateral movement near the end of the displacer. The sensor output was displayed on an oscilloscope to determine the peak to peak vibration amplitude and frequency. A second sensor was installed to measure the amplitude of any mounting plate (frame) movement to be sure that only displacer vibration was actually being measured. It was mounted just off the outside diameter of the mounting plate as shown in Figure 2.

The results from the mechanical test series are that the die post bearing gap was established at 100 microinches and a thin coating of low vapor pressure grease was applied - a compromise that restricted vibration sufficiently while allowing the bearing to run free without seizing. Lateral vibration amplitudes were approximately 0.003 to 0.004 inches peak to peak. A lower amplitude would have been preferred; however, the bearing seized because of thermal expansion when the bearing clearance was reduced to 60 microinches. The 100 microinch bearing clearance was used in the thermodynamic tests and pencil witness marks were drawn on the displacer before the thermodynamic tests in order to detect any rubbing between the MACOR^{TM} displacer and cylinder.



Fiqure 2. Mechanical Test Apparatus

IV. THERMODYNAMIC TESTS

Test Facility

The thermodynamic test facility was built using a frame from a CTI-CRYOGENICS model 1020 compressor package. The vacuum shell and radiation shield functions were provided by a CTI-CRYOGENICS Cryotorr^R-8 cryogenic vacuum pump operated by a model 350 refrigeration system. This shell was mounted on the frame so that the test cryocooler can be operated vertically. Besides being a convenient and economic test vehicle, the CT-8 provided the 80K radiation shield. This freed the upper stages of the MACOR^{TM} test cryocooler from the radiation shield heat load and allowed the potential for testing these stages with an electrical heat load independent of radiation loading.

The Gifford McMahon refrigerator had two stages of refrigeration, 80K and 20K. Careful attention was given to insulating the test cryocooler from the 20K stage. The 20K stage served the purpose of a limited amount of cryogenic vacuum pumping during the test.

Instrumentation included a diode and a heater on the test cryocooler fourth stage, thermocouples on the first and second stage, a radiation shield thermocouple, vacuum gages (thermocouple and ionization) and a cycle helium pressure transducer. Ammeters and voltmeters were used to monitor compressor motor performance, and heater power. Operational speed was measured by monitoring the cycle pressure oscillations on an oscilloscope. The 4th stage diode was a Lakeshore model DT500 silicon diode. A specially made wire wound heater was used. Thermocouples were copper constantan and the output was recorded directly on an Esterline Angus digital data acquistion system. Rough vacuum was measured with a Veeco T670 thermocouple gage and a Division 500 DV6 vacuum gage. High vacuum instrumentation included Veeco model RG830 and model RG1000 ionization gages. Cycle helium pressure was measured with an Entran pressure transducer, serial 26WOXM11, with transducer power supplied by a Lambda Electronics Model LPD-424A-FM power supply. A pressure gage was

installed on the crankcase of the compressor. The crankcase also served as the helium gas reservoir. A small amount of helium was allowed to leak through the die post bearing during each cycle to maintain the helium working pressure. Compressor motor voltage and current were measured with Hewlett Packard 3465A digital multimeters. Motor power was supplied by two Elgar model 501C power supplies - one with a 400 V insert serving as a signal generator with frequency control, and the other with a 400 SR insert serving as a power amplifier. A Tektronix 5103N oscilloscope was used to monitor the helium cyclic pressure wave.

Test Procedure

After assembly of the test cryocooler was completed, it was installed into the test facility. The cryocooler was charged with purified helium by first evacuating the cryocooler and then pressurizing it with approximately 50 PSIG of purified helium. The cryocooler was then operated for a few minutes in order to circulate helium and force any air or impurities toward the purge port. Then the evacuation, pressurization, and operation cycle was repeated five times in order to obtain the highest practical level of helium purity.

The vacuum chamber inside the CT8 vacuum shell was evacuated first with a roughing pump for about 2 hours. Then an oil diffusion pump was used to further evacuate for several hours. The CT8 cryopump used for cooling the radiation shield was then turned on and allowed to cool. The cryopump surface area array was removed because of space limitations so only a minimal amount of cryopumping occurred. In the event of helium leakage, the cryopump will not pump any appreciable amount of helium so the diffusion pump was used. Before the cryopump cooled measureably, the diffusion pump was valved off. The minimal amount of cryopumping was sufficient to achieve a vacuum of approximately 10^{-6} Torr. This was a good vacuum and an indication that the metallic coating applied to the MACOR™ cylinder was leak tight.

The test cryocooler charge pressure was adjusted by applying helium gas from a high purity cylinder to the compressor crankcase. Since the test cryocooler was not yet operating, pressure equalization between the crankcase and the displacer entrance took about 30 seconds because the crankcase helium required time to leak through the die post bearing to get to the displacer entrance. This method was used to replenish helium lost through any leaks in the operating chambers. After setting the pressure, however, there were no detectable leaks noticed during the test series.

Thermocouples were checked before the start of the test. Then the test cryocooler was started. The speed was set using the cyclic pressure wave frequency as indicated on the oscilloscope. Data, taken approximately at 15 minute intervals, included 4th, 2nd, and 1st stage temperatures, charge pressure, helium pressure wave amplitude, radiation shield temperature, pressure in the vacuum shell, motor voltage and current, and cryocooler speed. Operation was continued until the cryocooler reached a steady state condition as indicated by stage temperatures.

After steady state had been demonstrated (this required a couple of hours), charge pressure, speed, or 4th stage electrical heat load was changed to a new operating point and a new test to equilibrium conditions was conducted. Data again was recorded at approximately 15 minute intervals.

Changes in the mylar insulation (on or off), and transfer tube diameter required cryocooler disassembly. Therefore, after one of these parameters was changed, the test procedure was restarted from the beginning.

Experimental Results

A summary of the performance of the cryocooler as represented by the lowest 4th stage temperature is shown in Table 1. Data representing the trends of operating speed, charge pressure, presence of mylar insulation, 4th stage electrical heat load, and transfer tube diameter are shown in Table 2.

TABLE 1: SELECTED THERMODYNAMIC BEST-OF-TEST DATA

DATE	T_4,K	T_2,K	T_1,K	CHARGE PRESSURE, PSIG	SPEED, RPM	4th STAGE ELEC.LOAD, WATTS	MYLAR INSULATION	TRANSFER TUBE DIA. INCHES
12/02/82	122.0	162.4	211.7	76.5	2000	0	ON	0.093
12/03/82	117.6	157.2	205.8	83.2	1500	0	ON	0.093
12/14/82	118.7	-	216.2	68.3	1967	0	ON	0.093
12/15/82	118.4	-	217.1	68.3	1967	0	ON	0.093
12/16/82	118.6	162.4	217.1	67.4	1538	0	ON	0.093
12/17/82	99.3	149.5	209.9	108.9	1967	0	ON	0.055
12/20/82	128.9	173.9	223.4	108.9	1500	0	ON	0.029
12/21/82	97.6	148.7	207.6	116.3	1666	0	ON	0.055
1/06/82	95.4	146.6	204.2	120.5	1666	0	OFF	0.055

TABLE 2: THERMODYNAMIC TEST DATA TREND SUMMARY

DATE	T_4,K	T_2,K	T_1,K	CHARGE PRESSURE, PSIG	SPEED, RPM	4th STAGE ELEC.LOAD, WATTS	MYLAR INSULATION	TRANSFER TUBE DIA., INCHES
PARAMETER - SPEED								
12/16/82	124.4	166.1	219.2	66.2	1200	0	ON	0.093
12/16/82	118.7	162.4	217.0	68.4	1538	0	ON	0.093
12/16/82	120.7	165.4	219.2	68.0	2000	0	ON	0.093
PARAMETER - PRESSURE								
12/17/82	120.2	165.1	218.9	68.3	2034	0	ON	0.093
12/17/82	107.1	156.1	214.4	104.7	1935	0	ON	0.093
12/17/82	106.6	156.8	215.8	128.8	1935	0	ON	0.093
PARAMETER - MYLAR INSULATION								
12/21/82	97.6	148.7	207.6	116.3	1666	0	ON	0.055
01/06/83	95.4	146.6	204.2	120.5	1666	0	OFF	0.055
PARAMETER - 4th STAGE ELECTRICAL HEAT LOAD								
12/16/82	120.5	165.3	219.1	69.1	2000	0	ON	0.093
12/15/82	123.8	164.3	217.4	67.4	2000	0.0484	ON	0.093
12/16/82	131.2	167.8	220.0	67.0	2000	0.1064	ON	0.093
PARAMETER - TRANSFER TUBE DIAMETER								
12/17/82	107.1	156.1	214.4	104.7	1935	0	ON	0.093
12/17/82	99.3	149.5	209.9	108.9	1967	0	ON	0.055
12/20/82	128.9	173.9	223.4	108.9	1500	0	ON	0.029

Cooldown of the 4th stage as a function of time for three representative days of testing are compared with the model prediction in Figure 3. Cooldown of stages 1,2, and 4 are compared with the model prediction in Figure 4.

Discussion of Results

The data of 12/2 and 12/3 were the first runs of the series. Disassembly after 12/3 revealed that the displacer was rubbing the cylinder on the 3rd and 4th stages because of misalignment during assembly. The rubbing did not appear very serious, but frictional heat can seriously degrade the low temperature performance. Accordingly, the cold finger was cleaned up and great care was given to aligning the cylinder over the displacer prior to performing the rest of the testing.

The trends of Table 2 indicate how the best operation of the test cryocooler was obtained. The optimum speed for lowest 4th stage temperature is approximately 1500 rpm. This trend does not appear to be strong at higher speed because the temperature only increased by 2K as the speed increased to 2000 rpm. However, at a slower speeds, the trend is much more pronounced. A speed decrease of 262 rpm produced a 4th stage temperature increase of 5.7K.

The 4th stage temperature decreased as charge pressure was increased up to about 105 psig. A further increase in charge pressure up to 120 PSIG produced almost no change in 4th stage temperature. The 1st and 2nd stage temperatures, however, decreased as pressure was increased from 68 PSIG to 105 PSIG and increased over the 105 PSIG to 120 PSIG pressure interval. Therefore, a performance optimum was indicated at about 105 PSIG.

A test was conducted with the mylar superinsulation removed to determine the effect of thermal conduction along the insulation on cryocooler performance. The CT-8 Cryocooler was holding the radiation shield at about 80K. When the mylar insulation around the MACOR^{TM} cylinder was removed, the 4th stage

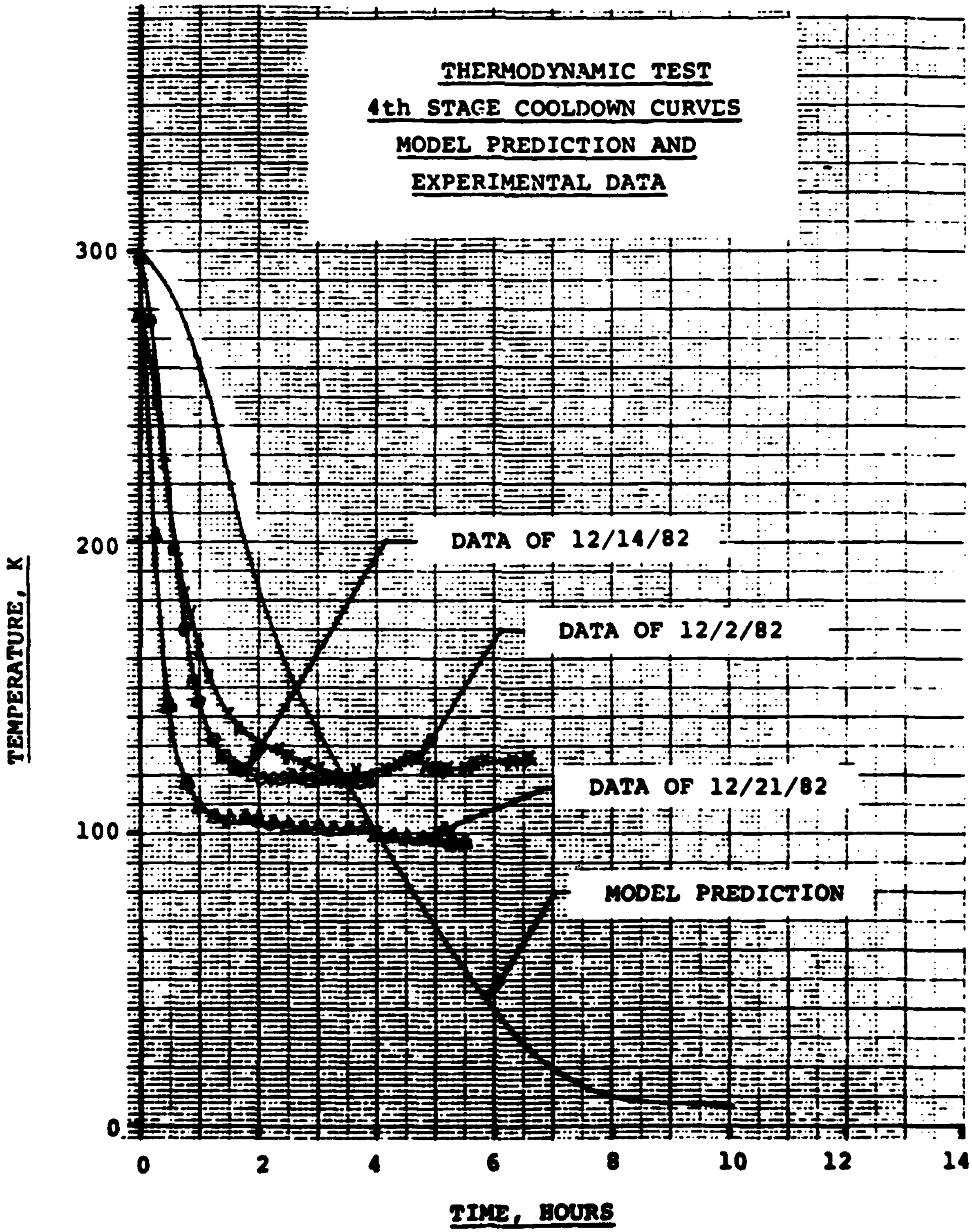


Figure 3: 4th Stage Cooldown Curves

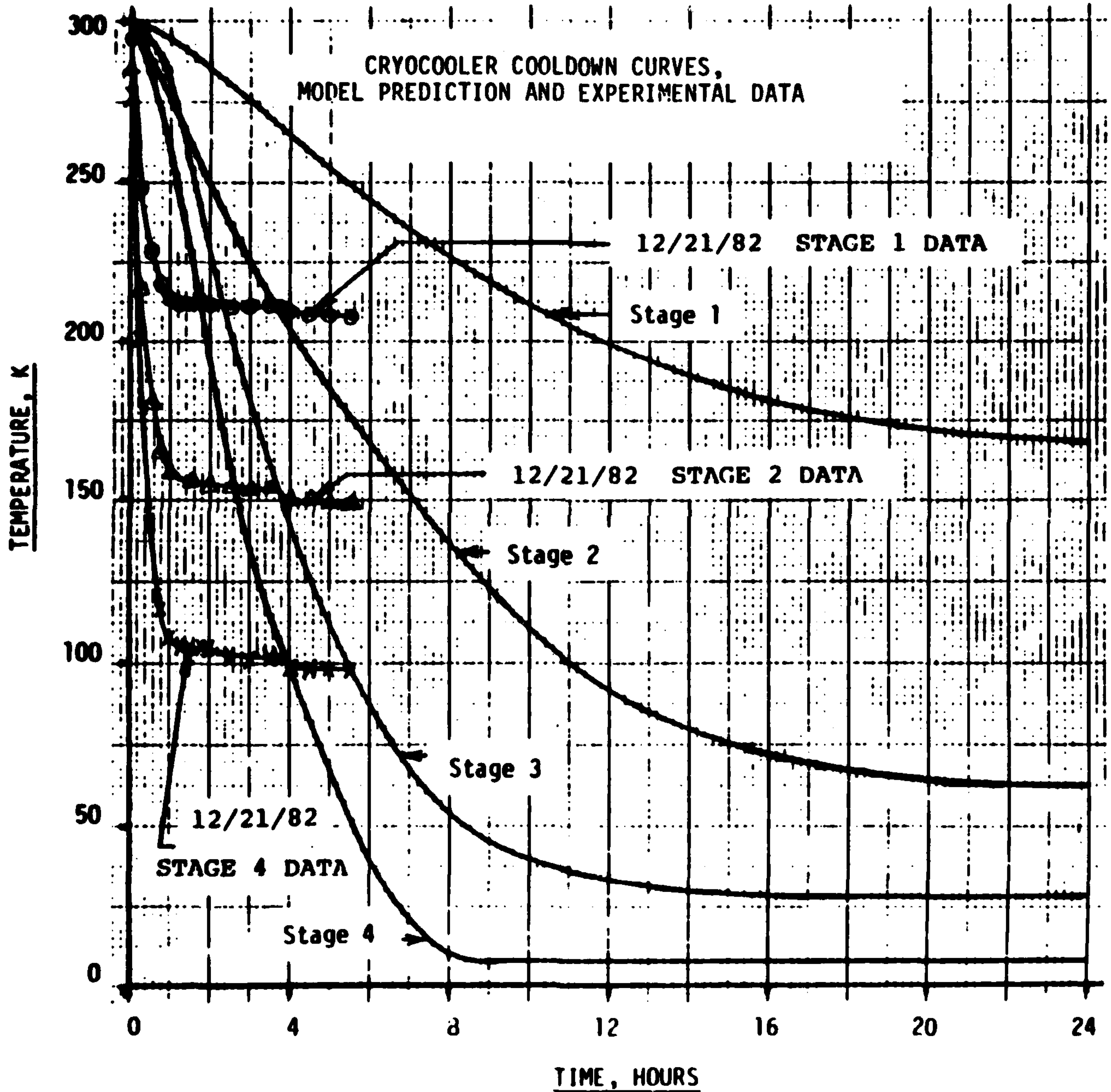


Figure 4: Cryocooler Cooldown Curves

temperature dropped from 97.6K to 95.4K. The change was due to a combination of more radiation heat transfer to the radiation shield and reduced thermal conduction up the cold cylinder because of the absence of the insulation. The 2.2K decrease due to removal of the insulation was not a significant change in performance.

A wire wound electrical heater attached to the 4th stage end cover was used to apply a thermal load to the cryocooler. The heater was physically located between the copper end cap enclosing the end of the 4th stage cylinder and a silicon diode temperature sensor. The amount of change in 4th stage temperature with thermal load was as expected except that the zero load temperature should have been less than 10K. The 1st and 2nd stage temperatures do not follow the same trend. These stages are thermodynamically more isolated from the electrical load.

A Stirling cryocooler is sensitive to the total amount of void volume associated with the working gas. The void volume of the transfer tube is part of the total void volume. The cryocooler is also sensitive to the transfer tube pressure drop. Therefore, the transfer tube diameter was parametrically changed to assess its effect on performance. Inside diameters used were 0.093, 0.055, and 0.029 inches. The data show that the void volume reduction in changing from 0.093 inches to 0.055 inches resulted in an increase in performance. However, a further reduction to 0.029 inches reduced performance. The pressure drop effect was dominant over the void volume effect in this range. Accordingly, the optimum performance was found with a 0.055 inch diameter transfer tube.

The trend study has indicated the effect of the five trend parameters on thermodynamic performance. Since the trend effect was not progressively optimized, i.e., the optimum result of one trend was not used as the starting point for the next trend, the absolute temperature associated with each trend does not indicate the trend value. Only the variation in temperature within each parameter variation is indicative of trend behavior. The important result is that variation of any of the listed trend parameters will not lower

the 4th stage temperature to 10K. It appears that a more substantial change to obtain more regenerator surface area per unit of helium flow will be needed.

Experimental 4th stage cooldown curves are shown on Figure 3 for three selected runs. The data of 12/14/82 and 12/21/82 have nearly the same shape; however, the 12/21/82 run started at 278K instead of 293K. Heat transfer to the radiation shield prevented complete warm up overnight from the previous run. Both curves took very nearly the same time to reach approximate thermal equilibrium.

The cooldown curve of 12/2/82 exhibited a smaller slope and therefore, took a longer time to reach equilibrium. This appeared to be due to the frictional heat generation between the displacer and cylinder due to rubbing between these parts on early test runs.

The cooldown curves shown in Figure 4 show the cooldown of the 1st, 2nd, and 4th stages on 12/21/82. At the end of 2 hours, the 4th stage appeared to be very close to thermal equilibrium. At that point the cryocooler charge pressure was increased from 102 PSIG to 120 PSIG to improve performance. A slight downward slope of temperature with time resulted. After 4 hours, the 4th stage again appeared to be close to equilibrium. Then the speed was reduced from 2000 rpm to 1760 rpm and a slight performance improvement again resulted. The combined effect of the adjustments made the experimental temperature curves of Figure 4 appear as though the temperatures were constantly decreasing when, in fact, the cryocooler was very close to thermal equilibrium.

The best of test data shown in Table 1 indicate that the 4th stage temperature performance improved over the course of testing as indicated by the temperature drop from 122.0K to 95.4K. Still, the cryocooler could only cool to about 95K regardless of test apparatus adjustments. This temperature appeared to be about the limit of the thermodynamic capability of the test cryocooler. The theoretical model must be examined in order to determine the reasons why the cooler doesn't cool to the design 10K. It appears that more gap regenerator surface area is necessary per unit mass of helium.

V. CONCLUSIONS

The cold end "brassboard" experimental study has yielded several key conclusions:

- The current hardware can achieve a 4th stage temperature of approximately 95K with no net applied thermal load.
- Resizing will be necessary to reach 10K.
- The metallic coating applied to the outside of the MACOR^{TM} cylinder was successful in preventing helium permeation.
- The die post bearing supports the displacer adequately. Careful attention must be given to the manufacture of the bearing.
- The MACOR^{TM} construction operated mechanically successful.